Advancements in the U.S. Army Corps of Engineers Hydrographic Survey Capabilities: The SHOALS System

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Abstract *In an effort to modernize its hydrographic survey capabilities, the U. S. Army Corps of Engineers has undertaken a joint development program with Canada to construct and field test an operational prototype airborne lidar bathymeter system. The construction and field verification effort of this program began March 1990 with field tests scheduled for winter* 1993. *The system will be built by Optech, Inc., based on their design of the LARSEN 500, the only commercial lidar system current/y producing bathymetric surveys.*

The Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system will operate out of a medium-sized helicopter such as the Bell 212 *at approximately* 200 *meters altitude where the laser scanning system generates a swath width of just over* 140 *meters. System requirements dictate a laser operating at* 200 *Hz in both the blue-green wavelength for maximum water depth penetration and the infrared for surface interface recognition. Each laser shot strikes the water surface at a known location where its energy is partially reflected back to the receiver and partially transmitted through the water column. Transmitted energy undergoes scattering and absorption along its path to the bottom where the remaining energy is then reflected back to the receiver:*

The Transceiver, Positioning, Acquisition, Control and Display, and Ground Based Data Processing subsystems make up the SHOALS system. These subsystems have been designed, constructed, and currently are being laboratory tested prior to total system integration and field-testing. This article presents the system's design and discusses system use following development.

Keywords lidar bathymetry, hydrographic survey, airborne lidar.

Introduction

The U.S. Army Corps of Engineers is responsible for surveying over 40,000 kilometers of federally authorized navigation channels around the U.S. and invests over $40 million in hydrographic surveys annually in support of this effort. Presently, Corps hydrographic surveying is performed by small launch-type vessels (6 to 20 meters in length) coupled with acoustic fathometers and horizontal positioning systems. The existing fleet numbers over 75 vessels, of which the Corps owns approximately 50 and contracts for the others annually. Horizontal control for both is usually provided by a microwave range/range or range/azimuth system, and vertical control depends on standard fathometer calibrations such as bar checks coupled with tide or river gages and associated water surface elevation interpolation/ extrapolation techniques.

Due to this vast hydrographic survey requirement, in the early 1980s the Corps began investigating technologies that could augment existing capabilities at comparable cost and provide fast accurate surveys. In March 1988 the Corps began a cost-shared program with the Canadian government to design, construct, and field verify an airborne lidar hydrographic surveying system. The program is intended to build on experience gained by the Canadian Hydrographic Service in operating a similar system, the LARSEN 500, from a fixed-wing aircraft. The program is implemented through a joint Memorandum of Understanding under the U .S. /Canadian Defense Development Sharing Program. Optech, Inc., of Toronto, Canada is the contractor developing the system.

The first step in the development program was to determine if this technology, illustrated in Figure 1, was capable of meeting the Corps' specific needs and to produce a conceptual design. This effort was completed, with favorable results, and in March 1990 the program initiated the design and construction of an operational prototype Lidar system named the SHOALS system (Scanning Hydrographic Operational Airborne Lidar Survey).

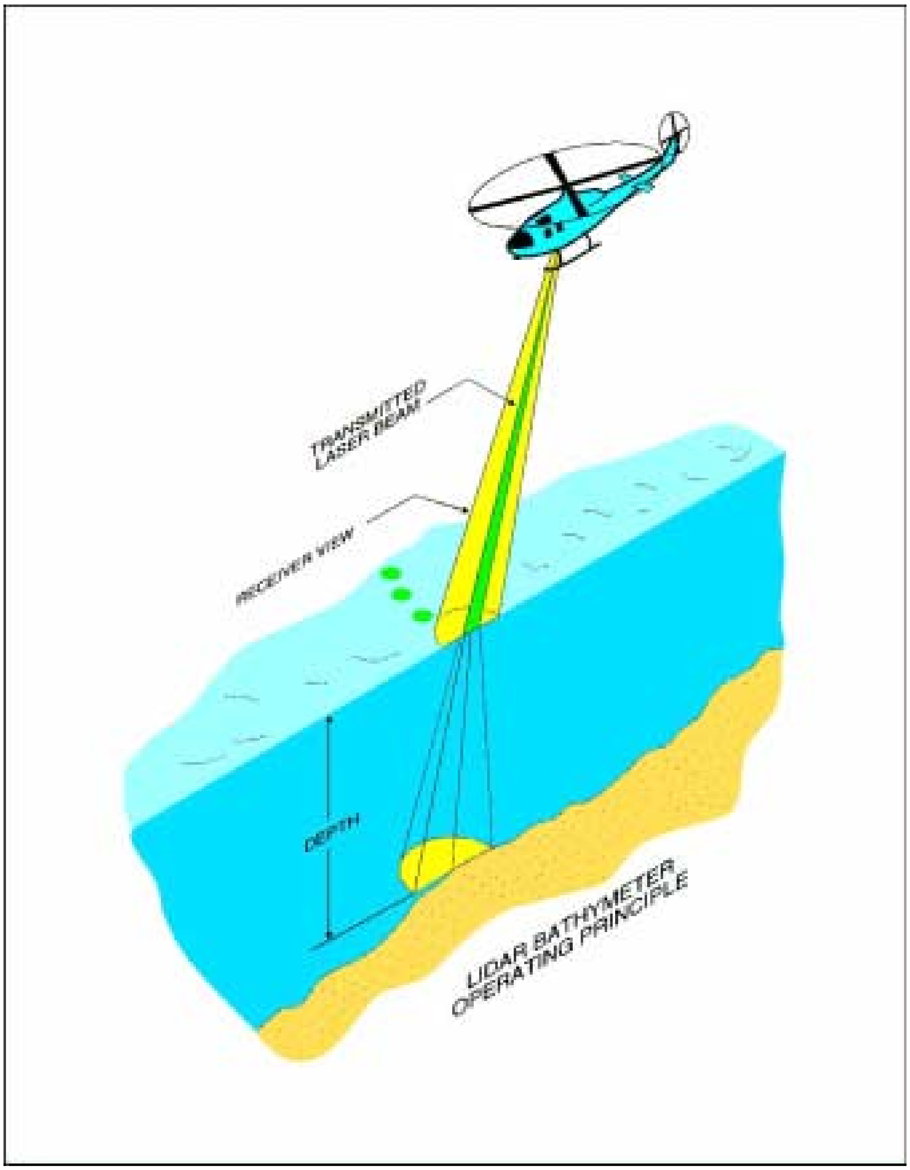

Figure 1 SHOALS operating principle

The design was formulated to meet specific performance requirements listed in Table 1. The resulting system is described in the next section, followed by a summary of the test plan. Once the construction and initial testing are complete, the SHOALS system will be demonstrated throughout the Corps of Engineers, which also provides the opportunity to characterize fully the system on a wide variety of project types, under a range of environmental conditions.

Table 1 SHOALS System Performance Requirements

Maximum depth	*Kd* > 3 in daytime, *Kd* > 4 at night*
Minimum depth	1.7 meters
Vertical accuracy	30 cm
Horizontal accuracy	6 meters
Sounding density	3 to 15 meters
Operating altitude	200 m
Operating speed	0 to 50 m/sec
Operating temperature	5 ° to 40°C
Data processing	5 hrs of processing for 1 hr of data
Aircraft	Bell 212
System mob/demob	8 hrs to install 6 hrs to deinstall

*Where *K* is the diffuse attenuation coefficient of water and *d* is depth.

System Design

The system design is divided into four subsystems: Transceiver; Positioning; Acquisition, Control and Display; and Ground Based Data Processing, which are illustrated in Figure 2.

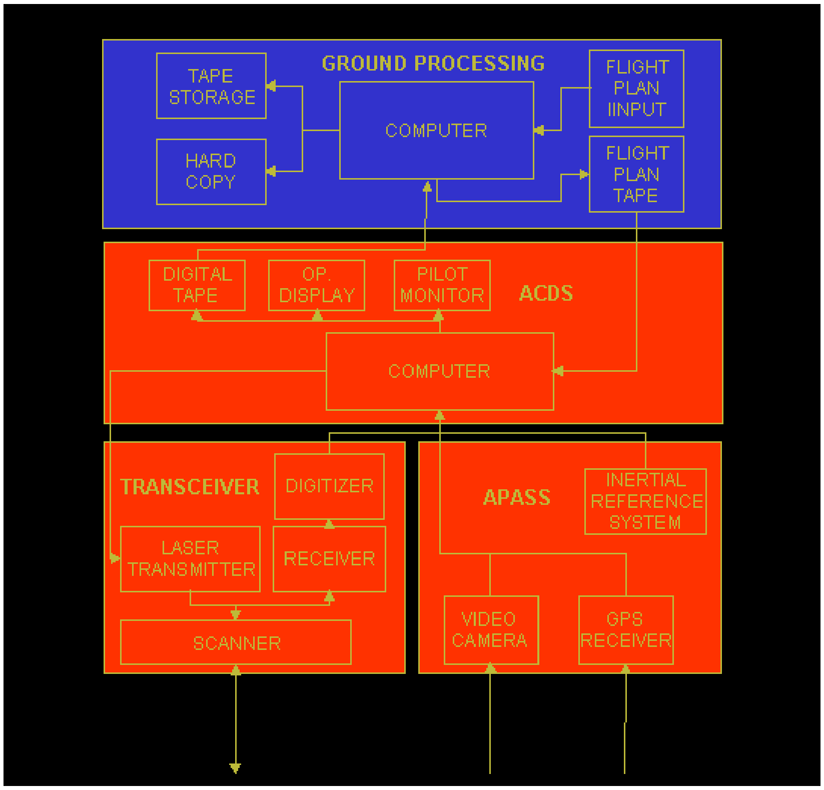

Figure 2 Block diagram for the airborne and ground-based subsystems

Transceiver

The Transceiver Subsystem (TRS) is the primary airborne subsystem consisting of the laser, scanner, receiver, digitizer, and external casing (for the SHOALS system, a pod). The TRS, see Figure 3, is mounted inside an environmentally controlled pod. The pod is mounted to the bottom of a Bell 212 helicopter between the landing skids and attached to the helicopter's main lifting beam. The function of the TRS is to transmit collinear infrared and green laser pulses in a defined scan pattern and to receive backscattered energy from these pulses to produce laser depth soundings and aircraft altitude information.

Figure 3 The transceiver subsystem. From left to right, receiver optics, receiver electronics, telescope, scanner, and inertial reference unit.

The laser is a 200 Hz Nd: YAG operating at a wavelength of 1064 nm (infrared) and frequency doubled to 532 nm (green). Laser output at both wavelengths is approximately 5 milli-Joules. The pulse widths for the 532 nm and 1064 nm wavelengths is approximately 6 ns and 7 ns, respectively. The operating temperature range is 0°C to 40°C.

The receiver includes a telescope, which is a catadioptric Cassegrain design with a 20 cm aperture and a field of view of approximately 0.05 radians as well as secondary optics. The detection system is composed of five detectors, including a gated photomultiplier tube (PMT), two avalanche photo diodes (APD) to detect 1064 nm radiation (IR1 and IR2), an APD to detect 532 nm radiation (green), and an APD to detect Raman radiation at 645 nm. The grated PMT detects bottom returns in depths greater than approximately 5 meters. The green APD is for sensing shallow depths ranging from approximately 1 to 5 meters.

Laser pulses backscattered from the surface are detected by four channels, namely, the Raman APD, the green APD, and the IR1 and IR2 APD. During post processing of the data, algorithms determine surface locations derived for the Raman, green APD, and IR1 channels and then select the appropriate value based on weighted logic. The fourth APD, IR2 is utilized for discriminating between land and water return signals. The polarization in the IR2 receiver is adjusted 90 degrees to that of the outgoing radiation and IR1. A comparison of the return signal amplitude from the two receivers is made to determine if the sounding was in water or on land. Reflected energy from the water surface tends to remain polarized in the same direction as the incident light. Energy reflected from land tends to depolarize and thus by comparison of the IR1 and IR2 channels land/water can be discriminated.

The scanner, developed by SAAB Instruments, scans the laser in a 180-degree arc across the forward direction of the aircraft. The scanner uses feedback from an inertial reference unit, rigidly mounted to the TRS, that measures aircraft roll and pitch information needed to produce a uniform depth sounding spacing on the water surface. Sounding spacing in both the forward and side-to-side directions are selectable and programmable by the system operator and may be modified to support each survey mission's objective. The nominal scan rate is 3 Hz, or 3 arcs per second with a scan width of approximately 140 meters (aircraft altitude of 200 m). This produces a sounding spacing of 5 meters between each laser shot with an aircraft speed at 50 knots. The scan width can be adjusted from 5 to 70 percent of the aircraft altitude.

The pod is designed to house the TRS and the inertial reference unit outboard of the aircraft in an environmentally controlled atmosphere. The TRS is vibration isolated from the pod at four points along each side of its length and attached to the pod enclosure. The enclosure consists of an aluminum honeycomb core laminate structure and two aerodynamic fiberglass end cones. It has a window on the bottom to allow laser transmissions to pass through and a remotely operated door over the window that closes to protect the window from damage during take off and landing. On top of the pod is an access hatch for maintenance.

The helicopter requires specially designed landing skids that provide approximately a meter and a half clearance under the aircraft to allow the pod to attach underneath and along the centerline. The pod is approximately three meters in length and weighs about 250 kg. An umbilical cord runs between the operator console and pod, connecting the TRS with the computer, laser cooling, and power supply.

Aircraft Positioning and Auxiliary Sensors

The aircraft positioning and auxiliary sensors functions are to collect information from the Global Positioning System (GPS) and inertial reference system to determine aircraft position, attitude angles, vertical accelerations and to provide a video image of the area being scanned.

Horizontal positioning for the SHOALS system is provided by the Global Positioning System. Two ASHTECH Rangers, which are capable of tracking up to 12 satellites each, provide horizontal position to ±6 m. The two receivers are operated in a differential configuration, and position correction factors are unlinked, in real time, to the airborne system using a VHF radio transmitter. Position data are passed to the pilot reference system and processed in real time to update the pilot guidance display. The data are also recorded for later post processing.

A Litton LTN-90 inertial reference unit provides aircraft attitude, including roll, pitch, and heading and vertical accelerations. The unit supports four functions: (1) it provides aircraft roll and pitch data to the programmable scanner, which then compensates for the aircraft's motion to produce a uniform sounding spacing on the water surface; (2) it provides aircraft velocity data for interpolating aircraft position in between the GPS data updates, in real time; (3) vertical accelerations are used to remove aircraft motion, which is necessary for the surface wave correction applied to the soundings during post processing; and (4) it provides roll, pitch, and heading information, which is used during post processing in the determination of the horizontal position of each sound- mg.

Included as an auxiliary sensor is a video camera mounted in the TRS pod. The purpose is to record a video image of the area being scanned. This provides the post processing operator with an image should anomalous data be encountered well after the survey mission has occurred. The operator is able to relate a specific laser shot to a specific video frame to determine if an object such as a vessel or small land feature was the cause of the anomaly. The video system consists of a color Hitachi camera and 8 mm Sony recorder that have been ruggedized for the aircraft environment. The video monitor also provides the operator with a real-time picture of the area being scanned, thus providing an added safety element; the operator can disengage the laser prior to flight over a populated stretch of navigation channel.

Acquisition, Control, and Display

Central to the system is the Acquisition, Control, and Display subsystem (ACDS), which provides operator interface to the SHOALS system and monitors and controls the airborne system. The ACDS provides five functions: data storage, airborne interface, pilot guidance, airborne depth processing, and system integrity.

The data storage function acquires data from all subsystems and manages that data as they flow through the system and are recorded onto magnetic tape. Data from four of the receiver channel along with position and attitude, system status data, and a host of additional information is acquired at a rate of over 360 Kbytes per second. Dual Exabyte tape drives are used to store data and provide the interface

between the airborne and ground-based systems. Following a survey mission, one tape is overnight express mailed to the post processing facility for immediate processing and depth extraction. The second tape remains with the system for safekeeping and backup.

The airborne operator interface displays system status information and controls all interactions between the operator and the system. The operator carries out two roles during a survey mission. First, the SHOALS system operator has the responsibility for conducting preflight planning and system calibration prior to a survey mission and monitoring system performance during a mission. These duties require in-depth knowledge of system technology to ensure the Lidar system functions properly. Second, the operator acts as chief hydrographer for the survey mission. This is accomplished through real- time quality assessment of data during a survey to ensure complete area coverage and that depths being collected are within the bounds of those expected. Both sets of levels of information are available to the operator through a point-and-click XWINDOW screen.

The pilot guidance function provides information on the aircraft's position relative to the survey area and individual survey track lines. The system accepts preflight mission planning data including survey area location, flight line specification, and system initialization settings. The mission data are then utilized to guide the pilot from the airport to the survey area and along each survey flight line. A single avionics monitor located between the pilot's and copilot's seats provides roll, pitch, altitude, heading, velocity, off-track error, and identification of a survey flight line for the pilot to use to guide the helicopter through each mission.

The airborne depth processing function calculates and displays preliminary water depth at 200 soundings per second, in real time to provide the operator a tool for quality checking data during a survey mission. The airborne algorithm utilizes a subset of the ground-based depth detection algorithm and is capable of producing depths accurate to approximately $\pm$ 1 meter. The purpose of airborne depth determination is only to provide the operator with approximate depths for assessing the general quality of data being recorded. The airborne algorithm does not include adjustments for tide, water surface waves, or propagation-induced biases that the more robust ground-based system calculates.

The last and perhaps most important function is system integrity. Through this function, the entire airborne system is constantly interrogated and monitored. System self-tests are performed on major components and error and failure messages are passed to the operator. A general status of key subsystems is monitored and continuously displayed on the operator's screen while other elements are periodically checked and if necessary, messages are passed to a window on the operator's monitor. In the event of a major error or failure, an emergency message interrupts the main screen with a warning.

Data Processing

The ground-based Data Processing System (DPS) includes the hardware and software necessary to post process the airborne survey data and extract water depths. The processing platform is a SUN IV workstation with Exabyte tape drives and color laser printer. The software is divided into three functional areas: (I) Data stripping where data are down loaded from the airborne system in asynchronous format. The first function of the DPS is to remove the data and resolve it properly in time and space and input the data in a relational data base management system. (2) Automated data processing assigns a horizontal position to each laser sounding, which is processed to compute a depth that has been corrected for water optical biases, surface waves, and tides. (3) A manual processing system to allow operator interface to interrogate individual laser soundings as well as system parameters used by the depth detection algorithm to calculate depth.

The depth detection algorithm is the most computing intensive element of the DPS. The algorithm performs a variety of housekeeping functions associated with each survey mission by calculating information such as survey area, SHOALS system settings specific to an individual survey mission, and other functions necessary for depth determination. Following housekeeping and initialization, the

algorithm scrutinizes individual surface and bottom returns from two of the surface channels and the two bottom channels to select surface and bottom times. Based on these times, a depth is computed. The algorithm computes mean water level by determining aircraft vertical motions from the inertial reference unit output and slant range calculated from the surface laser return. A position for each depth is interpolated from the GPS position data.

The final output from the DPS is an XYZ data set in ASCII format and associated with each depth and position, a confidence value based on several key parameters. This confidence value is weighted and derived from several system parameters but rolled into a single value for quick data assessment. The operator can select a confidence value threshold and view all data above that given threshold. The data output from the DPS is in ASCII format so that it can be easily ported to other systems and into applications such as volume computation, production of charts, or project design and layout.

System Testing and Operation

Immediately following laboratory and initial shakedown tests, the SHOALS system will be field tested over two months in the Sarasota, Florida area (anticipated start date March 1993). The purpose of these tests will be to determine if performance goals, described in the introduction, are met and/or under what range of conditions (given the conditions found in this area). Local water clarity varies from optically clear in the Gulf of Mexico to quite turbid around the city of Sarasota, located on the east side of Sarasota Bay. Bottom type varies as well, from sandy bottom to vegetated to muddy. During these tests, vertical accuracy will be compared with high-precision direct measure techniques such as a survey sled and with conventional fathometer surveys. Vertical accuracy with a survey sled is on the order of a few centimeters. Comparisons between the SHOALS system, sled, and fathometer will be useful in establishing the vertical accuracy between the SHOALS and fathometer systems. This is necessary because, following these initial tests, further depth comparisons will not use the high-precision sled.

To characterize fully the system and determine under what conditions the performance requirements can be met, the SHOALS system will have to be rigorously tested under a much wider range of conditions than those offered in the Sarasota area. Total estimated time is less than 200 hours at the end of the field tests conducted in southwest Florida. This is sufficient for determining contractual obligations associated with the specified performance requirements (vertical and horizontal accuracy, post processing time, etc.), but tests are constrained to a very limited set of environmental conditions. To characterize fully and determine its operational envelope, the SHOALS system must be utilized over a wide variety of conditions.

Also, the system must be integrated into the Corps and moved from developmental to operational within a reasonable time period. To support this integration, the SHOALS system and Lidar survey technology in general, will be demonstrated to the Corps through rapid utilization of the system. The SHOALS system will collect hydrographic survey data on existing Corps projects around the U *.S.* while ground truth fathometer survey data are collected concurrently. The two data sets can then be compared to demonstrate the SHOALS system's depth measurement accuracies for given Corps projects and geographic regions.

The demonstration missions will also produce ancillary field data that will be used to characterize the system based on environmental conditions. Information collected will be analyzed and used to optimize SHOALS system hardware settings (surface detection logic, optical filter settings, etc.) and software such as the depth detection algorithm (propagation induced bias estimates, diffuse attenuation/depth relations, etc.) over these different conditions and geographic regions.

Summary

Following these complete sets of tests, which will be several years in duration, the system will operate throughout the Corps of Engineers providing condition surveys in the regions where project depth and optical properties of the water are conducive to the technology. The performance capabilities of the SHOALS system will greatly extend the abilities of the USACE to undertake a broad range of survey applications more effectively. The SHOALS system represents a significant step forward in hydrographic survey technology compared to existing methods and a generational step in airborne lidar bathymetry operational capability. This new technology, however, will not replace the present acoustic systems but will be complementary. By utilizing each technology in situations best suited to its capabilities, the overall ability of the Corps to fulfill its survey mandate will be greatly enhanced.

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